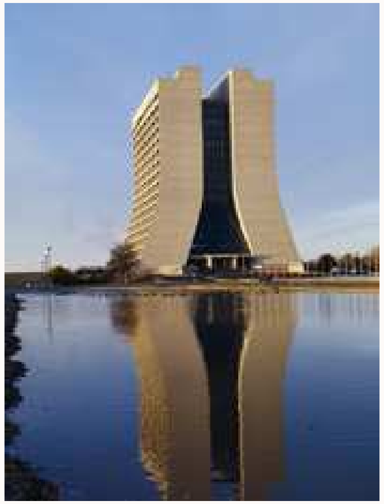
# Muon collider Monte Carlo tools?

[Muon collider mini-meeting @ FNAL]

Jan Winter

Fermilab

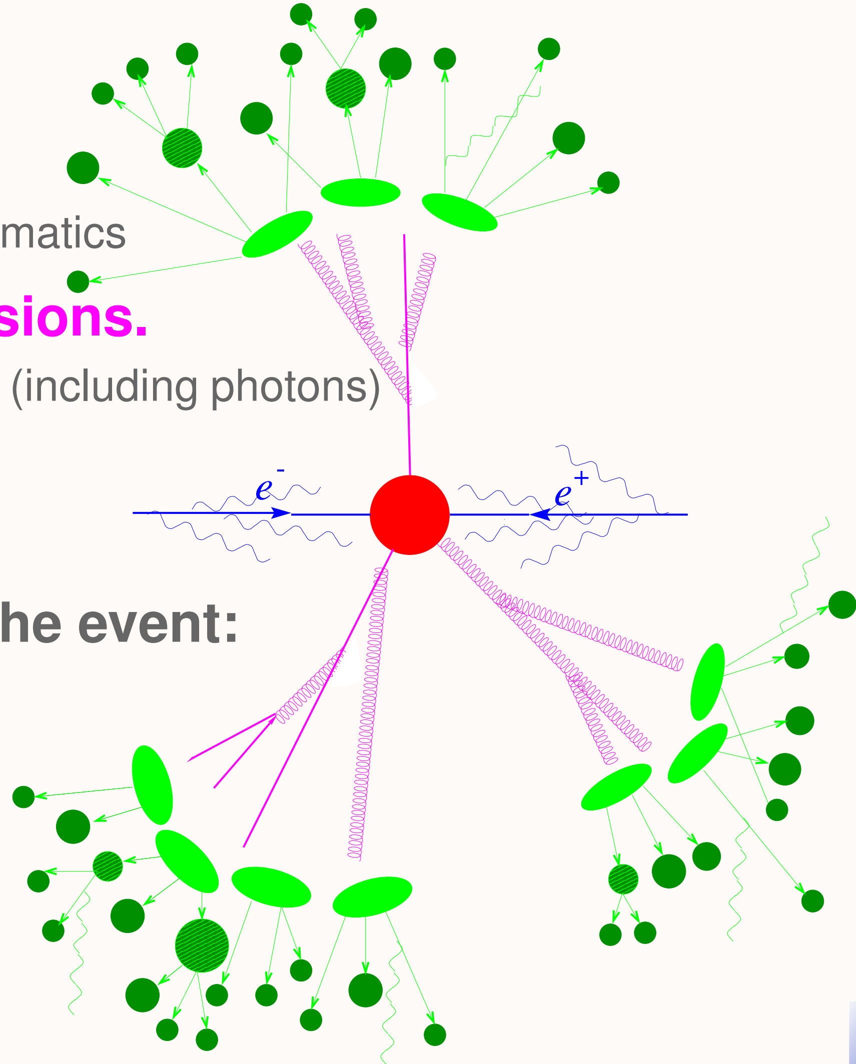


- **Phases of event generation**
- **Comments on hard-process simulation**
- **Comments on parton showers and ME+PS merging**
- **Comments on hadronization and decays**

**http://www.sherpa-mc.de/**

# Monte Carlo event generation

*Rely on factorization & decompose description of event generation into phases.*




- **Phases treated with perturbative methods:**
  - **Hard process: full ME description.**
    tree-level MEs for SM and BSM processes, parton-level kinematics
  - **FS parton showering: multiple soft/coll emissions.**
    resum to all orders large logs related to soft/coll singularities (including photons)
  - **ISR and beamstrahlung.**
    What can we learn/adopt from electron–positron colliders?
- **Phases of the non-perturbative evolution of the event:**
  - **Hadronization: this is modelling.**
    conversion of partons into primary hadrons
  - **Hadron decays: effective models.**
    tau decays, additional photons in such decays

**Not available: reliable description of ISR and beamstrahlung effects at muon colliders:** *adjust or implement new solutions into existing Monte Carlo tools.*

# Monte Carlo tools for muon colliders

- *Any tool that worked for LEP potentially can be adjusted to muon collider needs.*
  *[To 1st order $e^+e^-$ and $\mu^+\mu^-$ initial states can be treated similarly.]*
- *Muon collider studies will benefit from any new technique developed to improve the description of LHC final states (NLO+PS matching, ME+PS merging, cascade decay treatments).*

- Need for hadron-level predictions → two main streams
  - full-fledged MC event generators *[Pythia, Herwig, Sherpa]*
  - specialized tools simulating a single event phase, thus, relying on interfaces (mostly to Pythia, Herwig) *[Alpgen, CompHEP]*
- Need for general interface formats → Les Houches accord(s)
- Need for parton-level (hard process) generators ...
  - hosting a variety of (modern) models *[(S)MadGraph/Event, CompHEP, Sherpa]*
  - easily extendible to include new models *[(S)MadGraph/Event, CompHEP, Sherpa]*
- Need for a good handling of decay chains initiated by massive SM/BSM particles and their subsequent showers
- *Muon collider studies will benefit since these issues are already of importance for the LHC.*

# Simulation of the hard process

- **General task** generate (unweighted or weighted) parton-level events according to the differential cross section at tree level

$$d\sigma = \frac{1}{\mathrm{F}}\, d\Phi\, |\mathcal{M}|^2$$

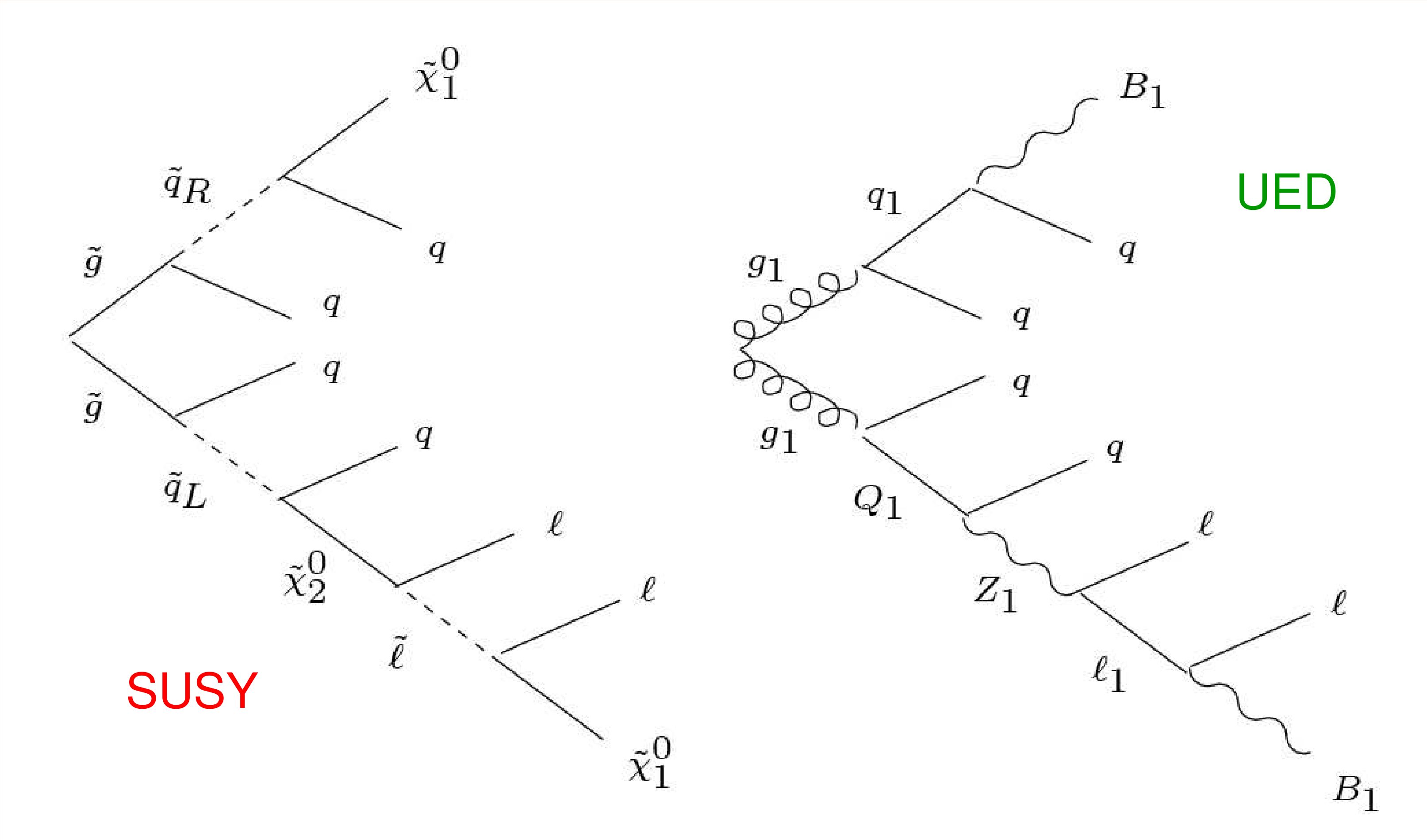
- **Two steps to take**
  - calculate the hard matrix element $|\mathcal{M}|^2$
  - integrate over/sample the phase space $\Phi$

- **Difficulties**
  - ME calculation becomes rather complex for increasing number of FS particles
  - highly dimensional phase space, integrands usually are peaked, cuts on kinematic variables

- **Number of good solutions**
  - MEs: analytic expressions *[Pythia,Herwig]*, Feynman rule methods *[(S)MadGraph/Event,Amegic]*, recursive methods *[Alpgen,Vecbos,Comix]*
  - Phase space: variety of methods to flatten out peak structures: VEGAS, multi-channeling, single-diagram enhanced integration

# Typical examples for BSM events

➡ *Similar signatures possible in SUSY and UED.*



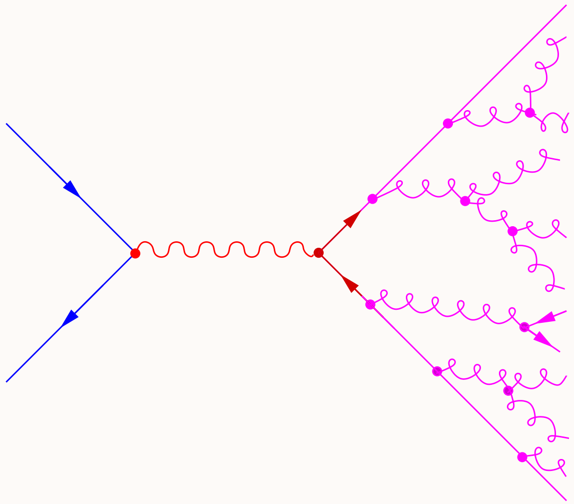

➡ *No way to avoid the appearance of jetty structures even that the only come from the final state as for the case of muon colliders.*

# Parton shower concept

**Simulate additional jet activity ... traditionally ... by parton showers**

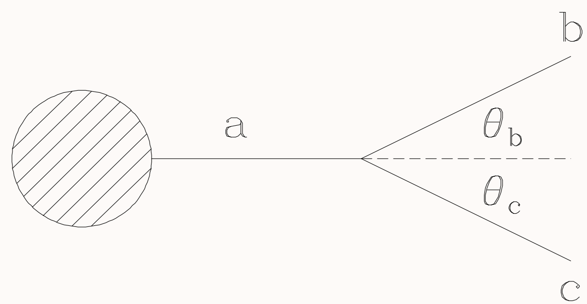
*[Pythia,Herwig,Ariadne]*

- soft/collinear parton emissions added to final states *[resum LLs]*
- partons are evolved down to hadronization scale *[ordering in virtuality, angle, $p_T$]*
- bulk of radiation and particle multiplicity growth is described by parton showering
- provides suitable input for universal hadronization models *[scales of $\mathcal{O}(1$ GeV$)$]*



- factorization – recursive definition in collinear limit

$$d\sigma_{n+1} \; = \; d\sigma_n \, \frac{\alpha_s(t)}{2\,\pi} \frac{dt}{t} \; dz \, P_{a\to bc}(z)$$



# Additional jets by parton showers?

➡ *For soft jets parton shower approach is valid and reliable.*

**Limitations:**

- lack of high-energetic large-angle emissions ➡ hard jet description unreliable
- semi-classical picture
- quantum interferences and correlations only approximated
- shower seeds are leading order QCD processes only

**Improvement:**

(1) *add next-to-leading order shower seeds*

*goes under the name of MC@NLO [Frixione, Webber]*

*promising POWHEG method [Nason et al.], positive weights, first application to $e^+e^-$ annihilation to hadrons exist [Latunde-Dada, Gieseke, Webber]*

(2) *describe first few hardest emissions according to tree-level MEs*

*goes under the name of ME+PS merging – (Lönnblad)CataniKraussKuhnWebber, MLMangano*

# Parton showers ... recent developments.

- New physics challenges (LHC), rewrites of PYTHIA/HERWIG codes **plus**
- enormous progress in the techniques of combining (N)LO calculations with parton showers led to an **intensive overhaul of existing formulations**.
- Efforts aim at ...
  - *achieving better analytic control.*
  - *gaining better understanding of systematic uncertainties.*
  - *providing (easier/more consistent) merging/matching with LO/NLO calculations.*
  - *going beyond common approximations (LL, large $N_{\mathrm{C}}$, include small-x)?*
- New $1 \to 2$ **splittings** showers, for PYTHIA *[Sjöstrand et al.]* and HERWIG *[Gieseke et al.]*, and new shower formulation based on Catani–Seymour dipole factorization *[Dinsdale et al.]*, *[Schumann, Krauss]*.
- Still other ways to identify/pick leading logs of multiple QCD emissions? **Yes. $2 \to 3$ splittings.** ➡ Lund CDM as implemented in **ARIADNE** is traditional.
  News: **VINCIA** *[Giele et al.]*. And, a SHERPA dipole shower *[JW, Krauss]*.

# ME+PS merging ... à la CKKW

- *combine parton-shower pros (soft emissions) +*
  *ME pros (hard emissions, quantum interferences, correlations)*
- *avoid double counting and missing phase space regions*

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**Divide multijet phase space into two regimes by $k_T$ jet measure at $Q_{jet}$.**

- tree-level MEs: jet seed (hard parton) production above $Q_{jet}$
- parton showers: (intra-)jet evolution $Q_{jet} < Q < Q_{\mathrm{cut-off}}$
- MEs regularized by $Q_{jet} < \; Q_{ij} = 2\min\{E_i, E_j\}(1-\cos\theta_{ij})$

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**Eliminate/sizeably reduce $Q_{jet}$ dependence.**

- identify pseudo shower history of MEs via backward clustering
- accordingly reweight MEs by combined $\alpha_s$ and Sudakov weight
- add showers to ME partons and veto emissions above $Q_{jet}$

# News on CKKW: heavy quark production + decays

➔ **Narrow width approximation** ➔ **full ME factorizes into production & decay parts**

- AMEGIC++ ... use its decay-chain operation mode
  projection onto relevant Feynman diagrams, Breit-Wigner intermediate particle masses
- APACIC++ ... enable production + decay showers based on massive splittings
  e.g. $\mu^+\mu^- \to t\bar{t}$ FS shower for tops
  e.g. $t \to W^+ b$ IS shower for top, FS shower for bottom
- CKKW ... separate and independent merging of MEs with extra jets & showers in production and any decay
- CKKW ... reweight and veto by respecting the factorization
- Schematically, e.g.: $\boldsymbol{\mu^-\mu^+ \to t\,[\to W^+ bg\{1\}]\,\bar{t}\,[\to W^-\bar{b}g\{1\}]\,g\{1\}}$

$$\mu^-\mu^+ \to t\,[\to W^+ b]\,\bar{t}\,[\to W^-\bar{b}]$$
$$\mu^-\mu^+ \to t\,[\to W^+ b]\,\bar{t}\,[\to W^-\bar{b}]\,g$$
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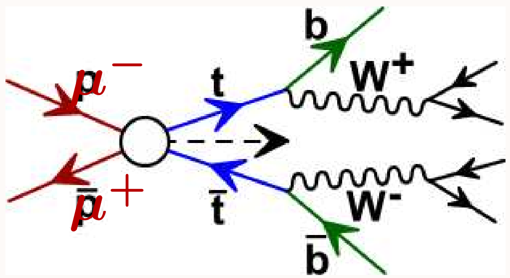
...




⇒ “CKKW 1-1-1”

# Apply to top pair production & decays at ILC

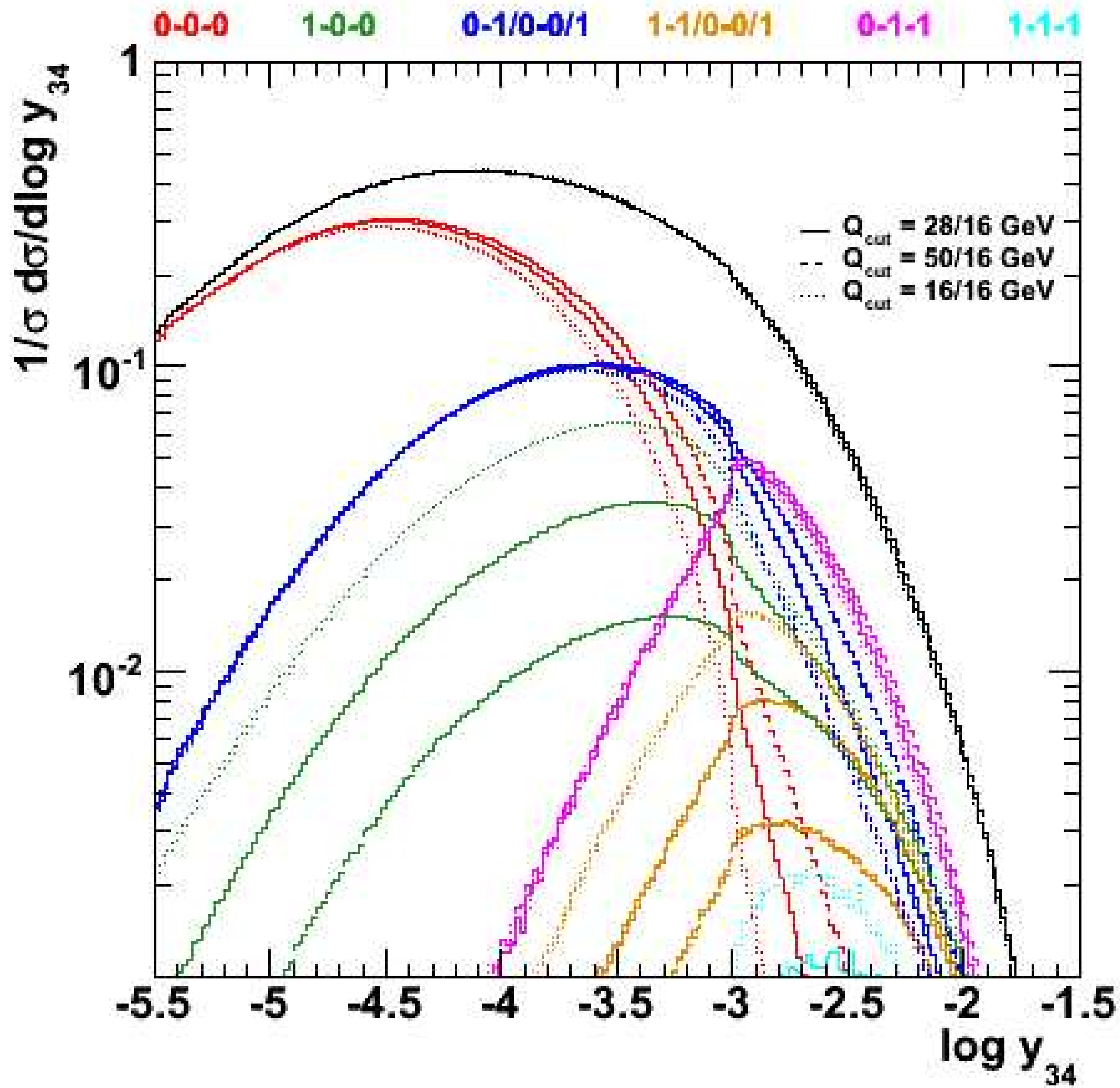
➡ **Some preliminary ILC results ...**

**$k_T$ diff. $4 \to 3$ jet rate**

*CKKW 1-1-1*

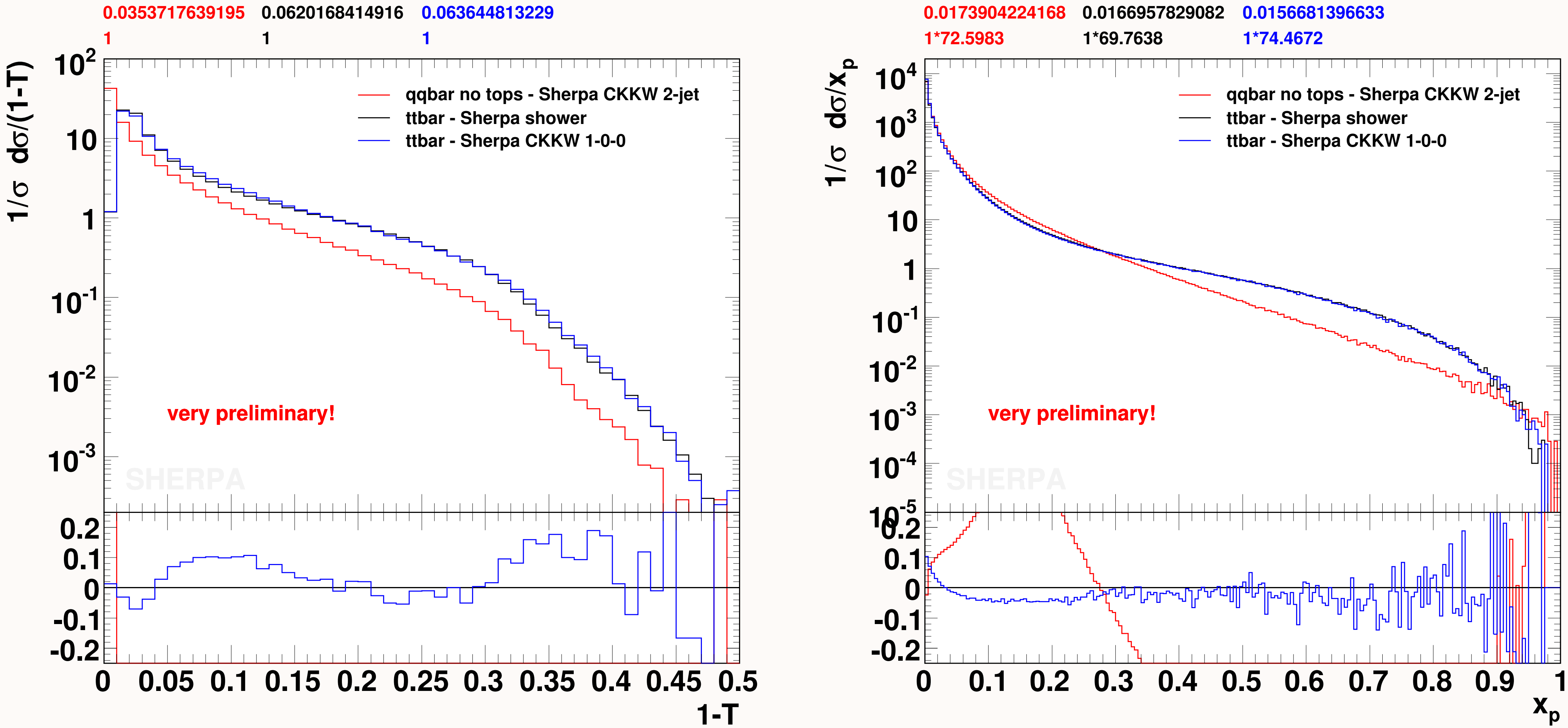
- **Vary jet separation**

*Sanity test for method: single contributions cooperate to give decently stable result.*



# CKKW mini test: top pairs at a 2TeV muon collider

- Sherpa: $\mu^+\mu^- \to t(be^+\nu_e)\bar{t}(\bar{b}jj) \to \text{hadrons}$ *vs* $\mu^+\mu^- \to q\bar{q} \to \text{hadrons}$
  - 1-Thrust and charged-particle scaled momentum distribution.




- *Numbers: charged particles $\sim 74$(LEP1: $21$), charged pions $\sim 60$(LEP1: $17$), charged kaons $7..8$(LEP1: $2$), protons $4..5$(LEP1: $1$)* ➜ *Upshot: WORKING approach !!*

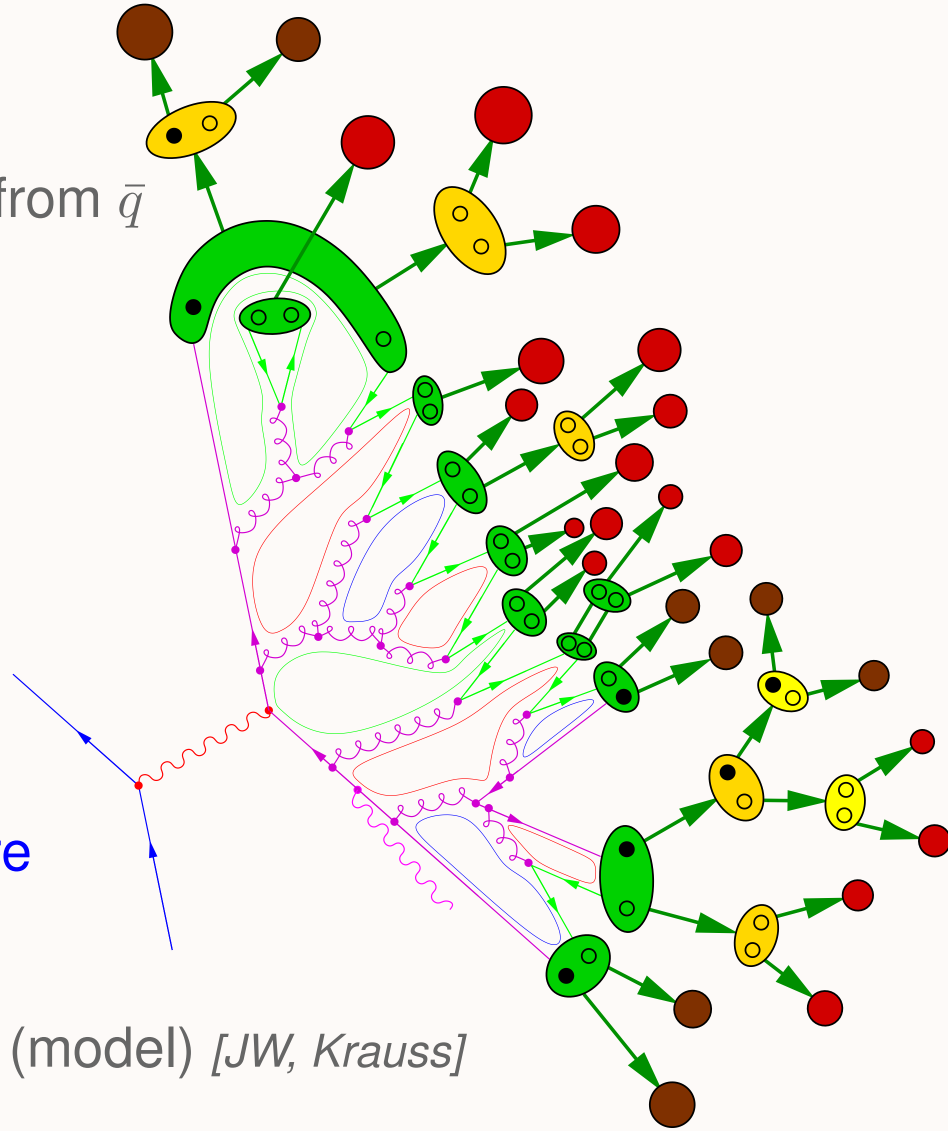
# Hadronization models

**scales of 1 GeV ... modelling the nonperturbative dynamics of a partonic system**

- Lund string fragmentation
- Cluster fragmentation

Soft effects $\Rightarrow$ low $p$ transfer
model primary hadron generation

- String:
- stringlike colour field between $q$ moving away from $\bar{q}$
- string breaks up into hadronic pieces
- gluons lead to kinked strings
- pioneers: Andersson, Sjöstrand
- Pythia is home of string model
- Sherpa interfaces to Pythia's string model



- Cluster: formation and decay
- **LPHD** and **preconfinement**
- **Locality** and **universality** $\Rightarrow$ modular structure
- pioneers: Field, Wolfram, Webber
- Herwig hosts cluster model
- Sherpa will have its own cluster hadronization (model) *[JW, Krauss]*

# Hadron decays

- Branching ratios (e.g. from PDG) as input.
- Decay kinematics à la $\mathrm{d}\Gamma(P \to p_1 \ldots p_n) = \frac{1}{2P} \cdot |\mathcal{M}(P, p_1 \ldots p_n)|^2 \cdot \mathrm{dLiPS}$
- From effective models + form factor models.
- General purpose Monte Carlos: strong efforts to provide streamlined and comprehensive decay frameworks *[Pythia,Herwig,Sherpa]*
- Specialized decay programs: EVTGEN *[Lange,Ryd]* and Tauola *[Jadach,Was]*
- Eg. in Sherpa:

➔ Example: $B^+ \to \pi \nu_e e^+$.